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COMMUNICATION BY ELECTRICAL STIMULATION OF THE SKIN

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A. Summary Page:

COMMUNICATION BY ELECTRICAL STIMULATION OF THE SKIN

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Summary

This report covers the first 18 months of a program of psychophysical research on communication by means of electrical stimulation of the skin senses. Progress was made on seven projects. Equipment development and modification, experiments on tactile sensory properties and tissue electrical characteristics, and a computer program are described.

Equipment. A system for accurate control of multi-dimensional electrical stimuli was devised and partly constructed. A prototype solid-state constant current stimulator was developed and built. An electrical thermode was designed and constructed for automatic control and rapid change of skin surface temperature under stimulating electrodes.

Sensory experiments. Effects of skin surface temperature, in four experiments on pain and touch sensitivity, were found to be still ambiguous. Electrical properties of tissue were investigated with pulses of direct current. Increases both in temperature and in current reduce tissue resistance. A computer program was written to simulate time-properties of voltage and current relationships within tissue; computer printout of simulated voltage pulses closely approximated oscilloscopic photographs, emphasizing the dynamic, rapidly changing resistive-capacitive nature of human tissue when stimulated electrically. Equal "loudness" contours, obtained with electrical stimuli of different physical properties delivered through electrodes of different sizes, indicate the nature of temporal and spatial summation in the touch system.

General

During the report period the project was moved with the principal investigator from Carnegie Institute of Technology to the Psychology Department of the University of Pittsburgh. In June, 1964, a M.S. thesis, entitled Spatial Factors in Electrical Stimulation of Touch, was completed under project support and submitted to Carnegie Institute of Technology by James R. Milligan.

Research reports were presented by the principal investigator (i) in October, 1964 to the annual meeting of the Psychonomic Society at Niagara Falls, Ontario, Canada, (ii) At M.I.T., May and June, 1965, to Sensory Aids research groups, (iii) informally, May, 1965 at an annual Bioengineering symposium, M.I.T., and (iv) as a member of the Academic Advisory Committee, in June, 1965 to the newly established Sensory Aids Evaluation and Development Center.

B. Detailed Report:

Introduction

Various attempts to devise cutaneous communications systems as supplements to vision and audition have been made over the past century. However, none has provided the speed or complexity comparable to information transmission through visual or auditory channels. This does not necessarily reflect limiting properties of the touch sense; rather, it probably reflects the failure to take best advantage of properties of touch perception.

To find whether cutaneous channels are effective for more than simple unidimensional warning information, or slow speech transliteration, it is essential to determine perceptual properties of stimuli varied systematically along temporal and spatial dimensions. One impediment for acquiring such knowledge has been poor stimulus control. Mechanical stimuli from vibrators are impeded in their movement by their own mass and by tissue factors. Electrical stimuli, as are light and sound signals, are capable of a wide range of temporal variation. Until recently, electrical stimulation of the skin readily excited pain and thereby saw limited use. Now, procedures (Gibson, 1963 a,b) have been worked out in detail for painless electrical stimulation of the touch system. Brief (0.5 msec) pulses of anodal direct current, when combined in short trains, at low pulse and train repetition rates, and through sufficiently large electrodes, delivered by constant current stimulator so that peak current does not vary with tissue impedance, can arouse reliably painless touch.

The remainder outlines progress on a program of psychophysical experiments with electrical stimuli aimed at contributing to basic sensory knowledge in three overlapping areas: (i) stimulus control, (ii) perceptual properties of touch, and (iii) cutaneous communication.

Projects

1. Multiple Dimension Stimulus Control System

The research to date has been designed to acquire data on basic sensory and perceptual phenomena mainly in their static states, one stimulus (or pair) at a time. Yet, the perceptual nature of absolute location phenomena, apparent motion, etc., all may change markedly in a dynamic situation where spatial and temporal patterns are changed rapidly and repeatedly over time. Thus, we devised a system to control multiple dimension stimuli. This system will be used in latter stages of the equal-loudness and apparent motion studies, and is required for a multiple-target tracking project planned for next year.

The system is designed around a photo-block paper tape reader to control and deliver combinations of multiple electric stimuli to several locations on the body, (see Figures 1 and 2). The general problem is to deliver rapidly a number of pre-programmed cutaneous electrical stimuli, differing as to several stimulus parameters as well as the number of electrode locations on the body simultaneously stimulated. The specially constructed block tape reader optically reads 96 bits of information each step, at a maximum rate of ten steps per second. There are six independent channels, each multiplexed to eight electrodes, for a total of 48 locations on the body. All logic circuitry has been breadboarded and checked out; two of the six channels are completed and have operated in full. Part of a draft for a manual of description and operation is appended to this report, along with schematics. A tape library of varied stimuli is being prepared.

2. Electrical Thermode

A thermoelectric element, using the Peltier effect to generate rapid temperature change proportional to the quanity of electricity passed through a junction, was attached to a machined brass electrode and built into essentially a calibrated beam balance in order to control electrode pressure. Attaching the proper heat sink to the upper plate of the element enables a delta-temperature between upper and lower plates of 55°C. Based on rough calculations, a 7-watt heat load is supplied by the tissues of the dorsal forearm to a one square inch area. The thermode has sufficient temperature capacity that, despite this load, the temperature can quickly be varied (15 sec/°C) from cold, through neutral, to warm, without being moved on the skin, a distinct advantage for threshold reliability.

3. Skin Temperature Effects on Touch and Pain Sensitivity

This is part of a larger effort to determine factors in electricity that underlie cutaneous stimulation so as to elucidate sensory mechanisms of operation.

Touch and pain thresholds were obtained in four experiments from several observers, under a variety of controls and conditions increasing the precision of measurement and temperature control.

For the first three experiments, skin surface temperature was varied by means of an electrical thermode attached to a brass two-centimeter diameter electrode, and measured with a small thermistor contacting the skin under the electrode. The thermistor was flush with the electrode stimulating surface, thermally and electrically insulated from the electrode by RTV-102, room-temperature curing silicone rubber compound. Temperature was displayed digitally, the continuously active display being stopped momentarily by foot switch for reading. The temperature time-constant of this "digital thermometer" was a rapid 2.5 seconds; thus readings maintained satisfactory pace with actual surface tissue temperature change. (The temperature of the electrode itself was monitored periodically also with other thermistors that were led to the multiple-input digital thermometer. One purpose, for example, was to keep track of the time-lag between electrode (i.e., heat-sink) temperature and skin surface temperature, following a large step-change of temperature to the electrode.

Experiment 1 and 2. Effects of temperature variation of 15°C to 45°C, roughly the tolerable range, on electrical touch sensitivity were found to be slight or nonexistent on the palmar base of the thumb and the dorsal forearm, both with single pulse and multiple pulse trains of current. Relevant conditions were: ascending method of limits, two subjects, anodal pulses, approximately two-centimeter diameter brass "active" electrode-thermode, temperature stabilization for at least five minutes at each temperature before start of threshold run, scrambled order on different days of each of five temperatures equally spaced from 15 to 45°C.

Since the rate of increase of a receptor potential with a constant amplitude stimulus varies directly with temperature, either the site of excitation of the touch system by electricity is directly at the nerve itself beyond this potential, or the temperature change is not getting to the receptors.

Experiment 3. Finding only slight effects on touch with electric stimuli might result either from the fact that effects indeed are slight or nonexistent thereby implying direct stimulation of the nerves themselves, or from the thermal diffusitivity of and the absorption pattern within the skin being such that the temperature changes at the electrode-skin interface are not mirrored over time within the receptor tissue layers.

As a first step in clarifying (for our purposes) the nature of radiant energy transfer through human tissues, the lateral temperature gradient was measured along the surface of the web between thumb and index finger. For five minutes, a 15mm. diameter electrode was maintained at 18°C., 15°C. below normal surface temperature at an ambient temperature of 70°F. The surface gradient obtained with a 5 mm. diameter thermistor is steep, the temperature only several millimeters from the edge of the electrode being within 2.8°C. of the normal temperature. Therefore, although it is likely that the heat rise within the tissues grows over time as the linear square root of the surface temperature, we need to determine the thermal inertial constants for inner tissues. Either subsurface temperature measurements should be done, or some other procedure used based partly on lateral surface gradients. The crucial question is the real depth at which little further temperature change occurs for large step changes in surface temperature.

As it is inconvenient to measure subcutaneous temperature so as to determine whether surface temperature change is reflected subcutaneously, the well-calibrated electrical thermode was temporarily shelved in favor of a brute-force technique for increasing the likelihood of obtaining temperature change at the receptor.

The subject inserted his entire rubber-gloved hand in a water bath previously brought to temperature and thereafter maintained within 2°C throughout each 30-45 minute experimental session. The 16mm. diameter stainless steel disc electrode and a thermistor was under the thin surgeon's glove. Other relevant conditions were: electrode taped in place with porous surgical tape, room temperature maintained within ± 5°F, counterbalanced temperature order, one temperature per session, five temperatures from 13 to 42°C, single-pulse electrical touch thresholds, ascending method of limits, seven to 21 thresholds per session, three sessions per temperature. Both electrical touch thresholds, and peak voltages at several fixed currents, were obtained. Briefly, threshold results were irregular and puzzling, two subjects showing roughly a two-to-one rise in touch electrical threshold from low to high temperature over the 28°C range, a change of the same magnitude being shown by the third subject in the opposite direction. Tissue resistances, calculated from voltage and current peaks, also in some respects were too irregular, and for other reasons suspect. One reliable finding was that tissue resistances fell with increasing temperatures.

Effects of glove pressures might be responsible for the anomalous results, as may be certain order and individual spot sensitivity effects. For the experiment, although apparently not well conceived, was at least systematic, and technically well executed, the variability not arising from insufficient trials for this sort of experiment. The matter is hereby put temporarily to rest, awaiting proper inspiration.

Experiment 4. Contrary to expectations following the pilot work, the results with stinging pain on hairy tissue suggest an approximately U-shaped function relating pain threshold as peak current to temperature, with maximum sensitivity to pain near room temperatures. However, pain thresholds were highly variable, despite extraordinary precautions in several experiments to obtain regularity by reducing effects of extraneous variables, implying either a basic instability in the pain mechanism, or further variables for study. Several observations suggest the latter, that thresholds vary from tissue properties independent of sensory mechanisms.

A stinging pain from electrical stimulation might simply reflect tissue breakdown from peak voltages developed across high resistance portions of the tissues that exceed the dielectric breakdown voltages, thus, causing pain from high current density at a spot.

Thus this notion (1) was followed up by monitoring separately four parallel segments of an electrode connected to the output of a single pulse stimulator (see Figure 3, and also next section), and (2) will be followed up by reducing tissue resistance and, thus, the peak voltage required to stimulate with a given peak current.

4. Electrical Properties of Tissue

The purpose was to determine electrical properties of tissue stimulated with pulses of direct current, and to establish relationships between tissue properties and sensory events.

The time-properties of voltage-current relationships within tissue were determined by recording the voltage response to current pulses of 1.0 to 50 msec duration delivered by constant current stimulator with high output impedance (effectively 200 megohms).

The voltage led through hairy and hairless tissue on five observers was examined as a function of (i) peak current amplitude, (ii) electrode size, and (iii) skin temperature. The voltage developed across the two electrodes (large indifferent electrode on the sole of the foot, small active electrode on either the dorsal forearm or the palm at the base of the thumb) was displayed on one trace of a Tektronix 561 oscilloscope, the current pulse displayed on another trace, and both photographed.

It was found that the current rises nearly instantly to maximum, but the voltage lags, as in a capacitative circuit, with the rate of rise, as well as the peak voltage at any given current, a function of the variables investigated. Therefore, (i) the peak voltage, and (ii) the time constant of voltage growth were measured from enlargements of the oscilloscope photographs as a function of the three variables.

Figure 4 is an oscilloscope photograph of a rectangular one-msec., one-ma. current pulse being delivered to the palm through a 16mm. diameter electrode. The oscilloscope is displaying the voltage developed across a small resistor in series with the tissue, and therefore is measuring the current. The center photograph of a second trace shows simultaneously the voltage developed between the two electrodes by the constant-current stimulator in order to achieve and maintain one milliampere of peak current. The top photograph is the voltage from a lower amperage pulse. Notice the onset-rise-time differences between the two voltage pulses.

Pulse width was increased substantially to permit the voltage of low current pulses to reach peak, owing to long rise times. Figure five is an oscilloscope time-exposure photograph displaying voltage pulses from five constant current pulses of different durations, from 0.5 to 2.5 milliseconds. It is clear that voltage onset-times do not vary with pulse duration.

Experiment 1. Effect of current amplitude on Tissue Resistance Results were: (1) as current increases from 0.05 to 5.0 peak milliamperes, tissue peak resistance decreases, initially precipitously, then more slowly with further current increase. Figure 6 shows tissue resistance separately for hairy and hairless forearm tissue (roughly nickel-sized active electrode, large indifferent electrode under the sole of the foot.) The time-constant of voltage rise (Figure 7) falls with increasing current in the same manner as peak resistance. The greater the current, the lower the tissue resistance, and the shorter the time for voltage to reach its peak. (One testable implication is a possible interaction between pulse repetition rate and peak current on pain thresholds measured as pulse train length. Low peak currents mean long voltage rise and fall times. Therefore, low current pulse trains of short

inter-pulse times might summate to pain rapidly as successive single voltage pulses become additive in the tissues, having insufficient off-time to fall to zero. Figure 8 shows one function from each of the previous two graphs plotted on log-log coordinates. Each is linear, to a first approximation, in these coordinates. The lines are fitted by eye. The relation between peak resistance and peak current is hyperbolic, with an exponent nearly unity; double the current, the peak resistance is nearly halved. The Time-constant falls similarly, although with a slightly greater exponent. The variation in time constant can be accounted for largely in terms of the fall in peak resistance, with the small difference between the two slopes attributable to tissue capacitance.

Thus, tissue resistance primarily, not membrane capacitance, is affected by the passage of current. It is reasonable to assume that most of the tissue change is in the surface layers, for they represent a large percentage of the total inter-electrode resistance. Future plans include (1) following up this hypothesis by manipulating surface tissue resistance, and (2) determining the relation between rapid tissue resistance changes and sensory thresholds. In a more practical vein, it is clear that it is not safe to stimulate human tissue with electricity, either for touch perceptual research or therapeutic purposes, without use either of constant current stimulators or rapidly acting current limiters. Also, to our surprise, owing to the large decrease in tissue resistance with the passage of, say, only 100 peak microamperes for 1.0 millisecond, peak voltage requirements for satisfactory constant current operation in the 0.1 to 5.0 milliampere region is clearly possible with peak voltages of less than 100 volts. This makes transistorized constant current units feasible for portable communication devices.

Experiment 2. Tissue resistance and Electrode Area. Tissue resistance and voltage-time constants were obtained at various current levels through electrodes of different areas. The data are not yet analyzed; in the meantime, this project has been expanded to include for future work the variables of electrode curvature, and linear pressure.

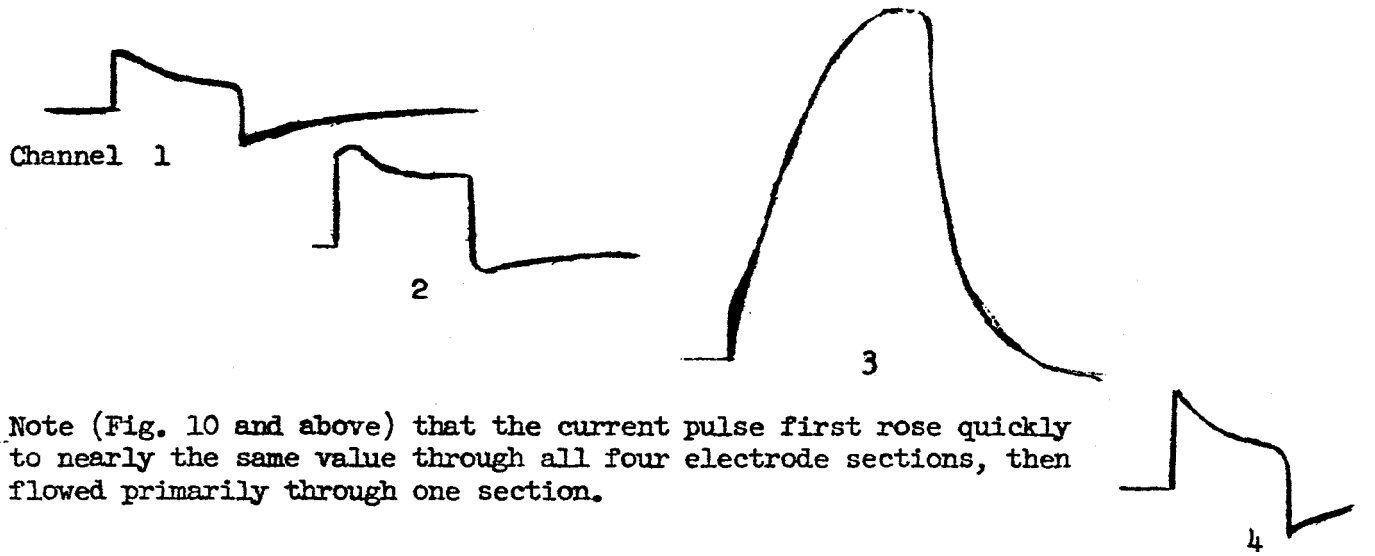
Experiment 3. Tissue resistance and Electrode Temperature. Figure 9 shows peak tissue-resistance under a dime-sized area on the palmar base of the thumb, as a function of electrode-skin interface temperature, at four single-pulse current levels. At low currents, with high tissue resistance, 30°C increase in skin temperature halves skin resistance. At higher current levels, tissue resistance driven to lower values, is less affected by a raise in electrode temperature. Above 5.0 ma. peak current, electrode temperature in the tolerable range has little influence on skin resistance under this electrode area.

Experiment 4. Tissue factors in electrical stimulation of pain. Occasionally, sometimes often on hairy tissues, with no obvious change in stimulus properties, painless electrical touch stimulation suddenly stings. Sometimes the pain does not disappear when the peak current is quickly reduced to one-fifth the value at which pain first appeared. Sometimes tripling the current upon the sudden appearance of pain will render the region relatively painfree for five minutes; other times, slightly increasing current levels increases the sting intensity. The irregularity of sting in our laboratory has a long history with regard to control by stimulus factors. This time we tried to determine the likelihood of tissue breakdown as underlying sting.

Under three inch diameter electrodes on the back, at stinging pain threshold with long trains of pulses, sting is usually reported as at a "point" and an investigator sometimes can localize with a pencil point a painful spot. Sometimes a small, red spot appears, usually near the edge of the area under a large, disc electrode. Often nothing untoward is visible in the area formerly under the electrode, however, even with low power (20 X) microscope.

The four sectioned electrode pictured in Figure 3 was used. Current was displayed on a separate oscilloscope trace for each of the four parallel electrode sections. Current was increased in small steps; however, the four oscilloscope current displays were maintained small and at the same size. One stimulator fed all (parallel) electrode elements; one large indifferent electrode was on the sole.

Several current steps prior to pain threshold, the current display for one segment would increase slightly. At pain threshold, the current through one electrode segment sometimes would be several times the peak values of portion of the current in each of the other three. Figure 10 shows a photograph of current through four parallel segments at pain threshold. (Three small current steps prior to this photograph, the four traces were within 10% of each other.) It is difficult to read the photograph because of the rise-time differences among channels. Spread out from left to right, the traces, top to bottom, would look roughly like this:



Note (Fig. 10 and above) that the current pulse first rose quickly to nearly the same value through all four electrode sections, then flowed primarily through one section.

The third trace increased during the time of the pulse to four times the peak values in the other channels. (This does not always happen through the same electrode segment.) It is clear that, sometimes at least, tissue resistance under a small segment of the electrode is reduced substantially, allowing current to be diverted (owing to the constant current nature of the stimulator) from other areas under an electrode, to pour through a small percentage of the total electrode-skin surface. We are now working on ways of using multiple electrode sections, separately controlled, and on ways of treating tissue, further to understand and control this problem.

5. Computer Simulation of Tissue Voltage Response

The nature of the voltage rise with a rectangular step of current, and its dependence on current, electrode size, temperature, and certain polarity effects not discussed here, imply a dynamic circuit with resistance and capacitances varying nonlinearly over time. Therefore, such circuits are difficult to solve with simple circuit theory. As a beginning, two computer programs were written to produce as output plots of voltage versus time. One program produced an approximation to our oscilloscope photographs of pulse voltage by plotting the appropriate exponential growth. The other, and more promising, used the SCADS subroutines at Carnegie Tech's computation center; SCADS = Simulation of Combined Analog Digital Systems. The final version of this program sets up an analog circuit that approximates a parallel R-C network with a large variable series resistor to assure constant current. The satisfying output of this program is a figure closely resembling some of out oscilloscope photographs (Figure 11). The next step is to fill in appropriate circuit element values.

6. Equal "Loudness" Functions

Threshold peak current (with 0.5 msec pulses) and the "loudness" of supra-threshold electrical stimuli vary with (i) train duration, (ii) repetition rate, (iii) electrode size, and (iv) the number of electrodes on a given body region (i.e., interelectrode distance). Thus, these variables cannot now be simply manipulated without simultaneously monitoring and adjusting peak current. Equal "loudness" functions have been obtained for these variables on several body regions. The observer matches the apparent intensity of one stimulus to that of another. Such functions will provide normative data that make it feasible in further experiments to manipulate these variables in combination over wide ranges using the stimulus control system with only minor unplanned variations in apparent intensity. The data are complete, have undergone (computer-aided) analysis of variance, and are being plotted.

7. Spatial factors in electrical touch stimulation

Threshold peak current for pulse electrical touch stimulation increases with increasing active electrode area. One purpose of this project was to determine the area=intensity threshold relationship over a broad range of electrode sizes with stimuli of different temporal properties. Touch threshold (i.e., current density expressed at the active electrode as mean total current per $mm.^2$ electrode area,) on the palmar base of the thumb was a decreasing hyperbolic function of electrode area with middle to large electrodes (18 to 576 $mm.^2$ area). Double the electrode area halves the current density, which relation indicates perfect spatial intensity summation, and emphasizes the relevance of current density to threshold measures. With smaller electrode areas, (18 to 2.25 $mm.^2$,) the rate of decrease in current density with decrease in electrode area was somewhat less, (an exponent of .7 rather than 1.0.) This might indicate reciprocity failure and thus a real spatial factor, although the possibilities were not ruled out either that the smaller electrodes required less threshold current because of factors related to greater physical penetration into the tissue, or possibly that the effective medium sized electrodes were larger than the steel elements alone owing to perspiration pools. The threshold dependence on electrode size does not vary with the number of pulses per stimulus. The master's thesis (Milligan, J. R., 1964) is on file at Carnegie Tech, and a manuscript is under preparation.

References during this period:

Gibson, R. H., Communication by Electrical Stimulation of the Skin, Report #1 in a series for the National Aeronautics and Space Administration, April, 1964.

_____, Communications by Electrical Stimulation of the Skin, Report #2 in a series for the National Aeronautics and Space Administration, October, 1964.

_____, Effects of Temperature on Touch, Pain and on Tissue Electrical Properties, Paper presented to Psychonomics Society, Niagara Falls, Canada, October, 1964.

_____, Tactile Displays, Informal paper presented to Sensory Aids Evaluation and Development Center, Massachusetts Institute of Technology, Boston, Massachusetts, June, 1965.

_____, Manual of Operation, including Schematics, for the Stimulus Control System (draft).

Milligan, J. R., Spatial Properties of Electrical Stimulation of the Skin, Unpublished Master's Thesis, Psychology Department, Carnegie Institute of Technology, June 1964.

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Gibson, R. H., Electrical Stimulation of Pain and Touch Systems, Nature, 1963a, 199, 307-308.

_____, Requirements for the Use of Electrical Stimulation of the Skin, Proceedings of the International Congress of Technology and Blindness, 1963b, 2, 183-207.

In Preparation

Gibson, Robert H., a chapter entitled "The Cutaneous Senses", to appear in Experimental Psychology, 3rd revised edition, formerly by Woodworth, R. S. and Schlosberg, H., Henry Holt and Co,, New York, 1955.

_____, Electrical Stimulation of Touch and Pain, invited paper to be presented to the International Symposium on the mechanisms of cutaneous sensitivity, March, 1966, Florida State University.

_____, The Electrical Stimulus for Cutaneous Stinging Pain, in preparation for submission to Science.

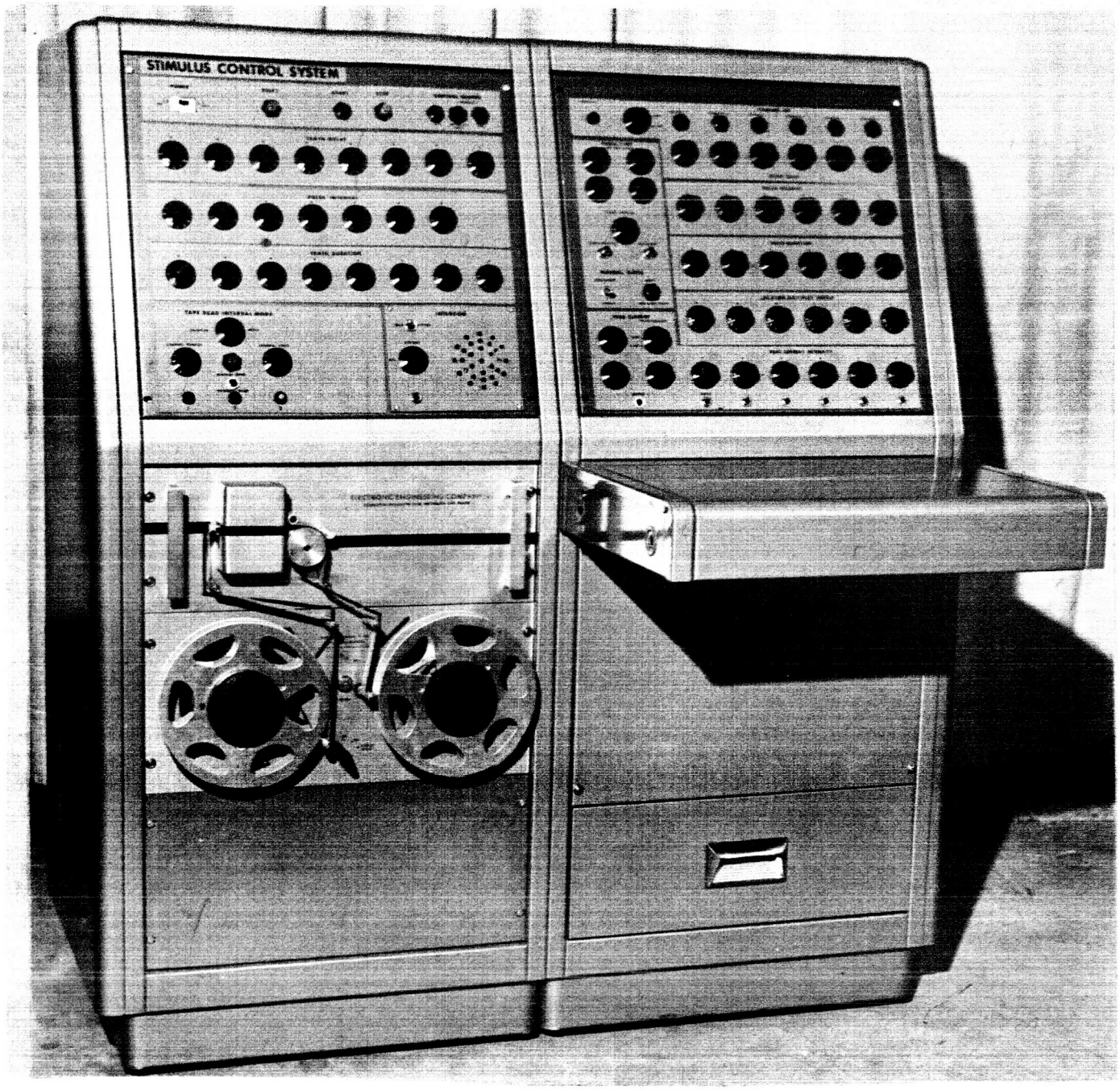

Figure 1. Stimulus Control System. The optical block tape reader programs combinations of brief direct current pulses, delivered by any combination of six independent channels to as many as 48 total locations. (Thus, for example, a matrix of 6 x 8 electrodes on the back might be used for experiments on spatial and temporal aspects of cutaneous pattern perception.)

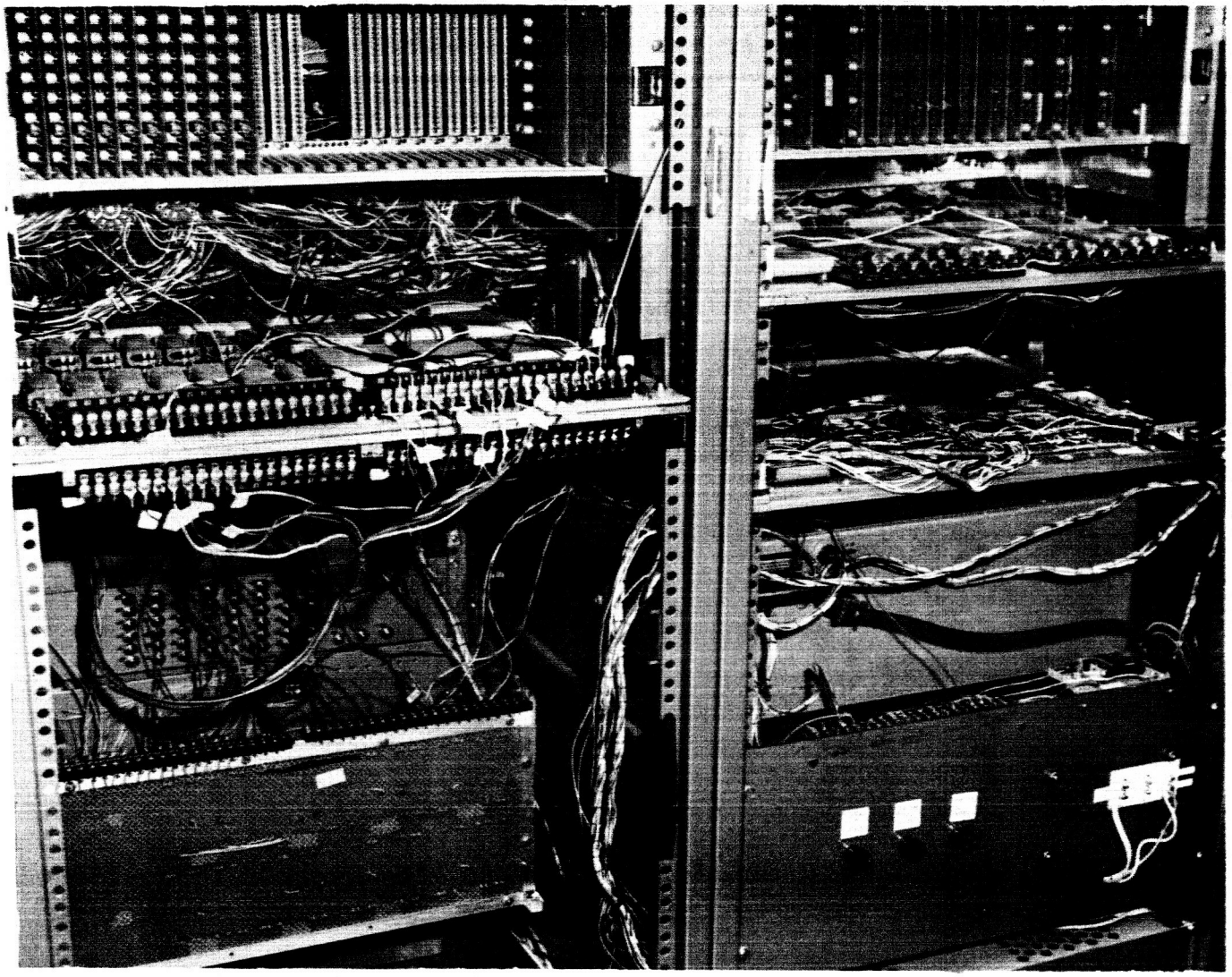

Figure 2. Innards of the (unfinished) Stimulus Control System. Note (top left, top right) the plug-in cards of computer quality transistor logic circuits that are quickly replaceable when necessary. Left upper center, the large horizontal tray is one of three holding specially constructed reed-relays. These have extremely rapid operating times of 0.5 to 1.0 millisecond. The gold contacts are hermetically sealed, with inert gas at reduced atmospheric pressure, all of which markedly increases contact reliability.

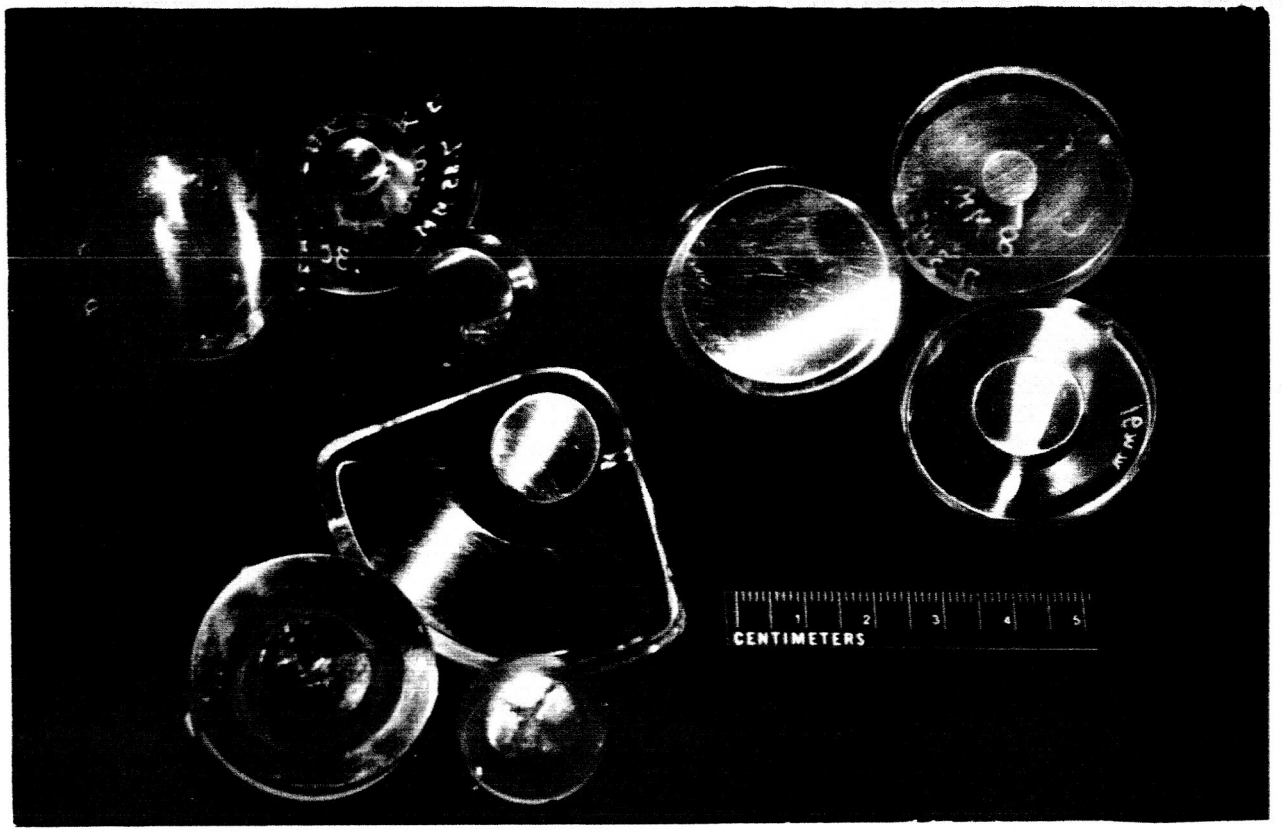

Figure 3. Electrodes. Arranged into three groups by function, these are polished stainless steel embedded flush into machined plexiglass. At the top right are flat electrodes of different sizes, used, for example, in the equal loudness contour study. At the top left are electrodes of different linear areas with different degrees of curvature, to be used in the pressure, curvature, area experiments. At lower left are samples with multiple conducting areas. The concentric and bat wing shapes are two of several electrode-pairs currently being tested to replace, for some purposes, the single active electrode and foot ground. The detail has unfortunately been lost photographically in the small one in the foreground of this group. Four highly polished and finished pie-shaped stainless steel sections are embedded flush in plexiglass for use in the tissue properties experiments.

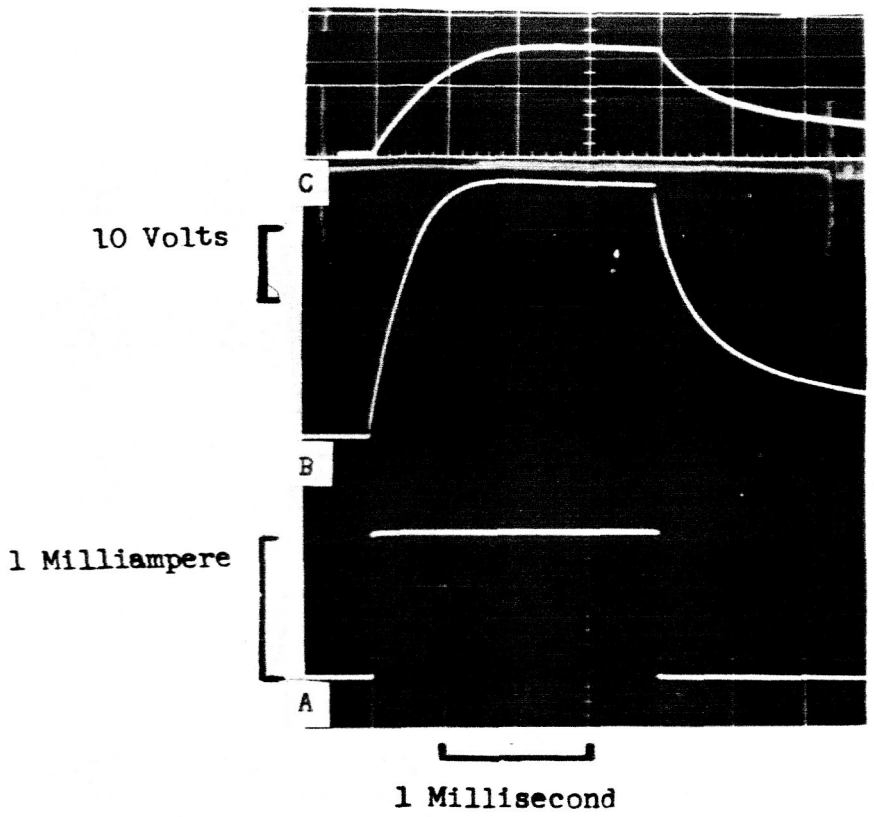

Figure 4. Oscilloscope photograph showing voltage and current during the course of stimulation by 2-millisecond rectangular electrical pulse from high-impedance constant-current stimulator. Sections a and b show current pulse and accompanying voltage pulse; c shows increased voltage rise-time from a current of reduced amplitude.

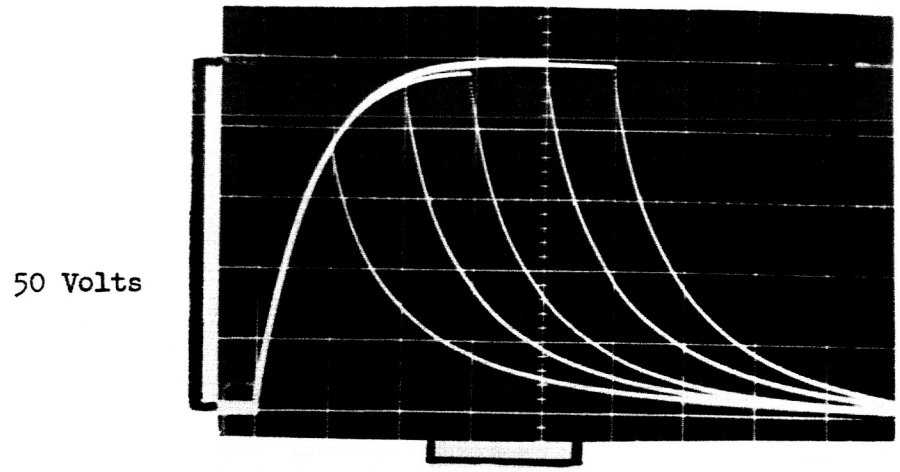

Figure 5. Time exposure oscilloscope photograph showing voltage pulses from constant current pulses of five different durations.

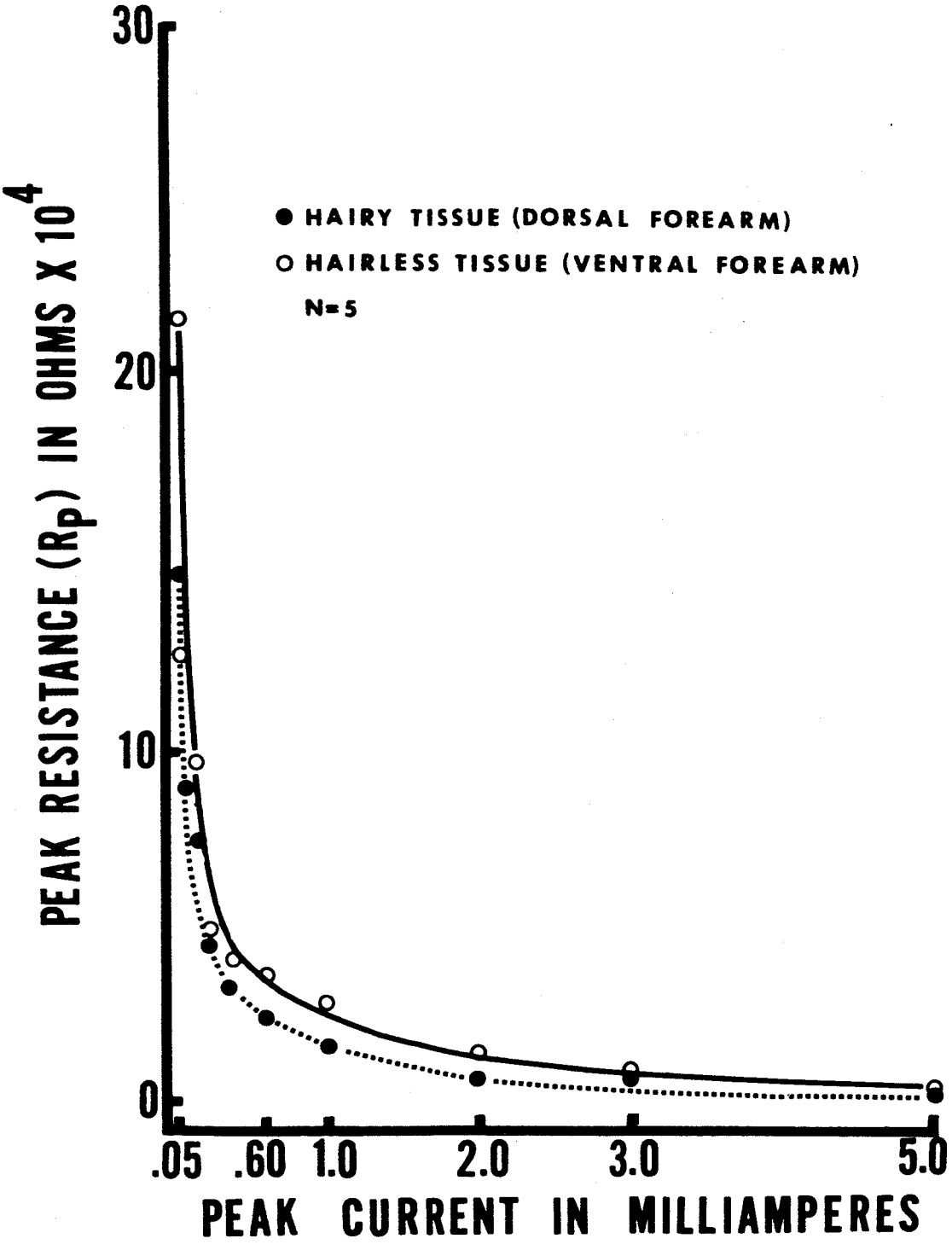

Figure 6. Tissue peak resistance as a function of stimulating current peak amplitude.

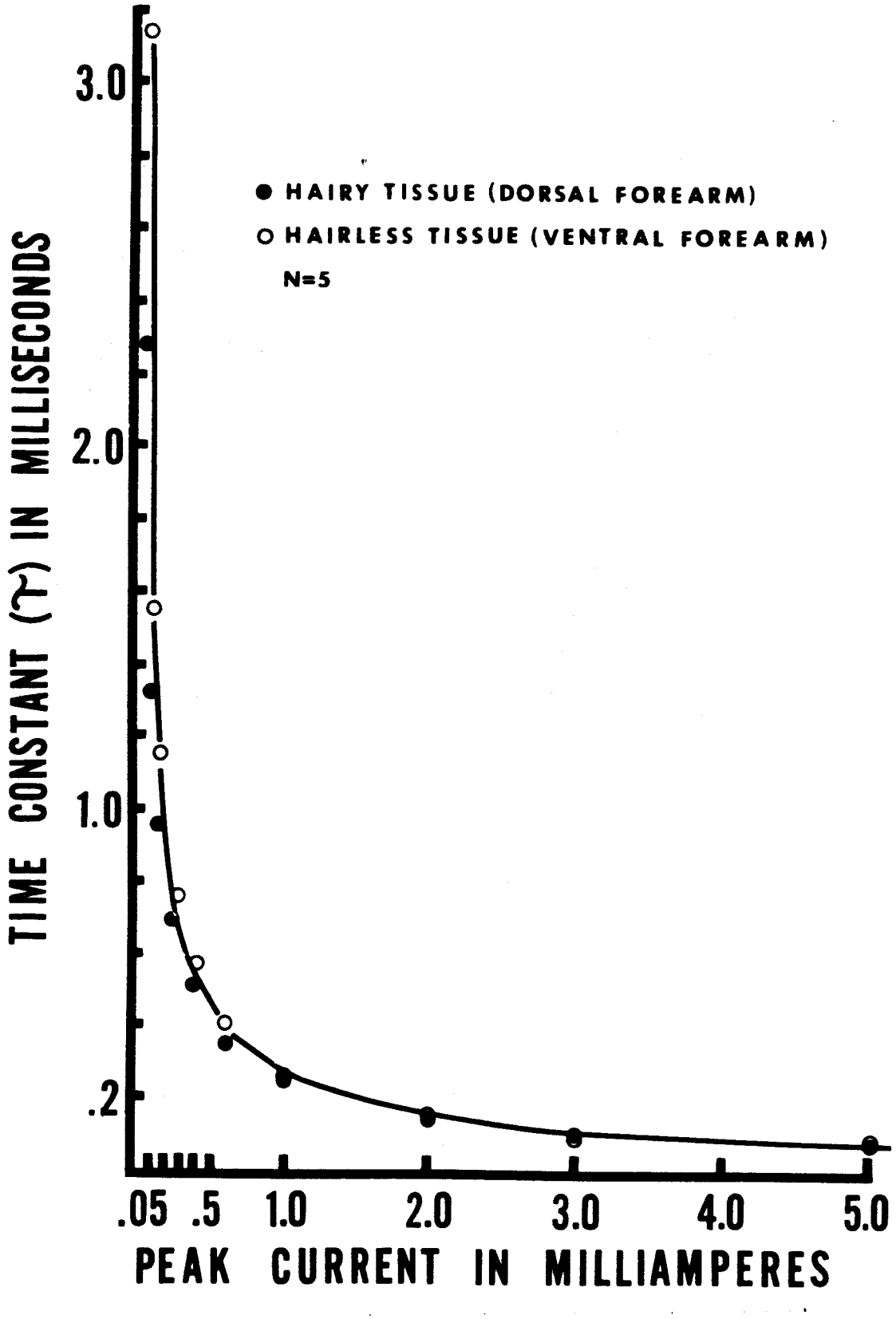

Figure 7. Time-constant of pulse voltage rise, as a function of stimulating current peak amplitude; high output impedance constant-current amplifier.

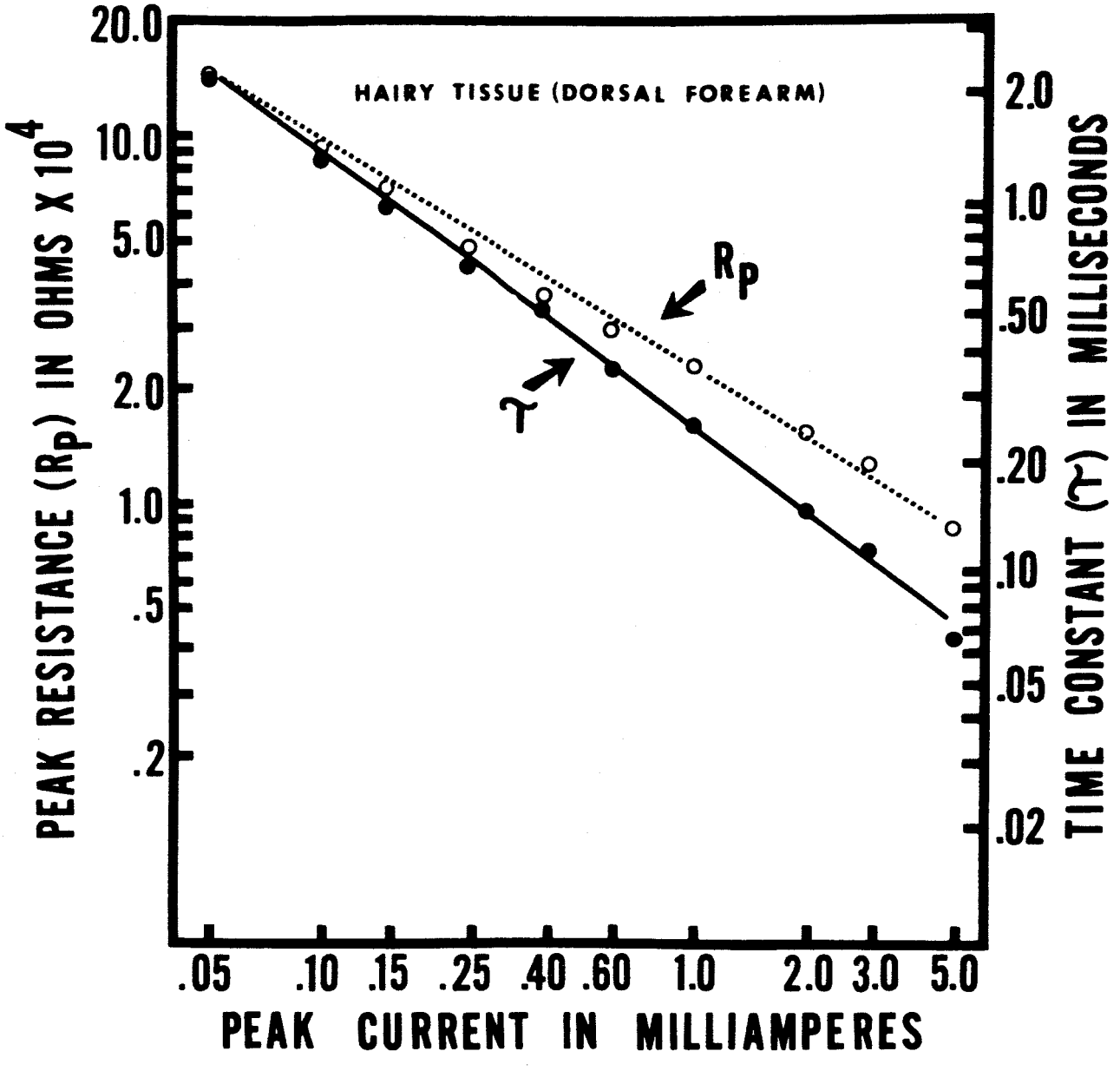

Figure 8. Tissue resistance and voltage rise time-constant, as a function of stimulating current peak amplitude; log-log coordinates.

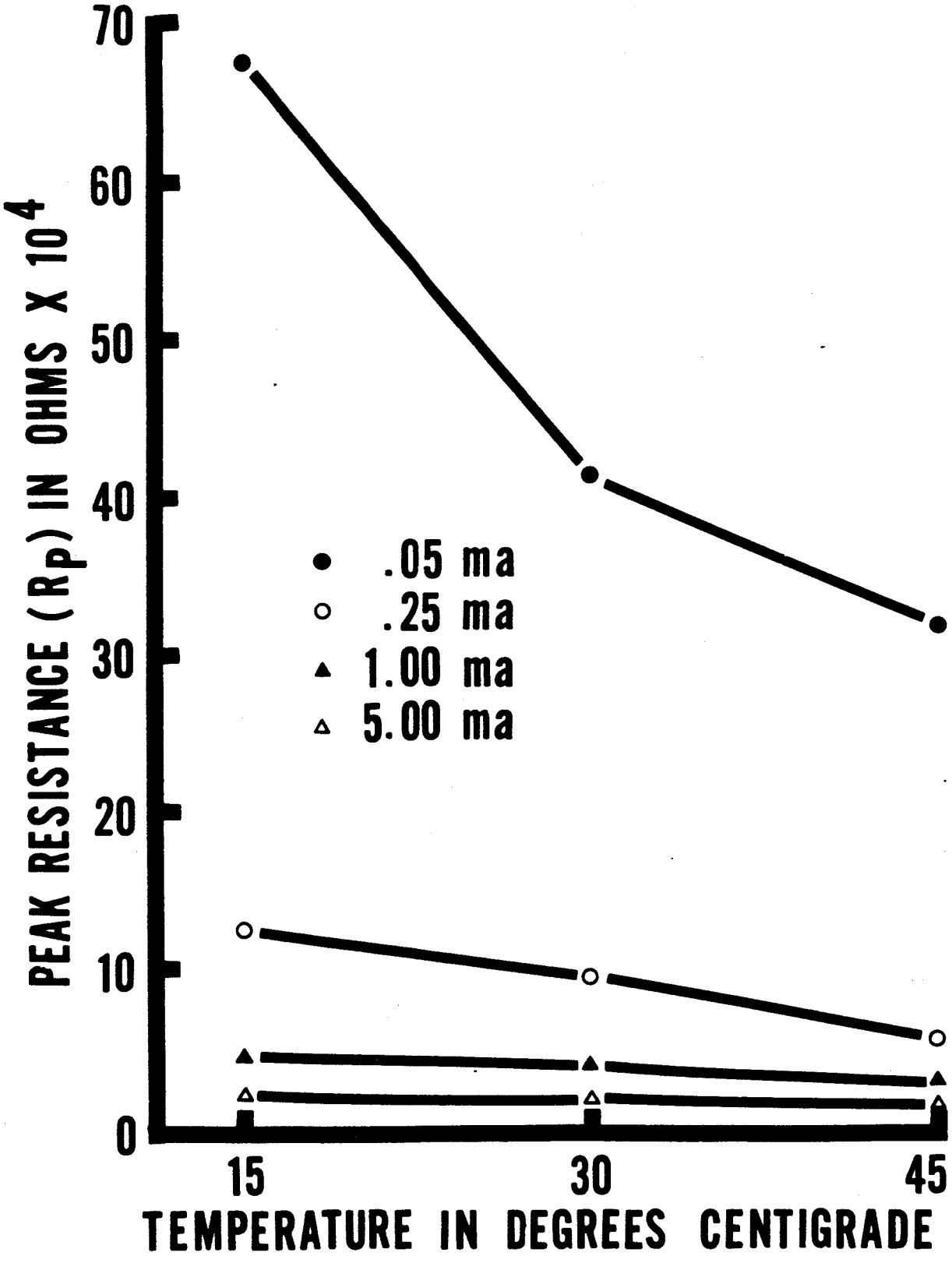

Figure 9. Effect of skin surface temperature on tissue resistance. Parameter is peak current. Peak final voltage measured at each current to obtain resistance values. Palmar base of thumb, 1 cm. diameter electrode-thermode.

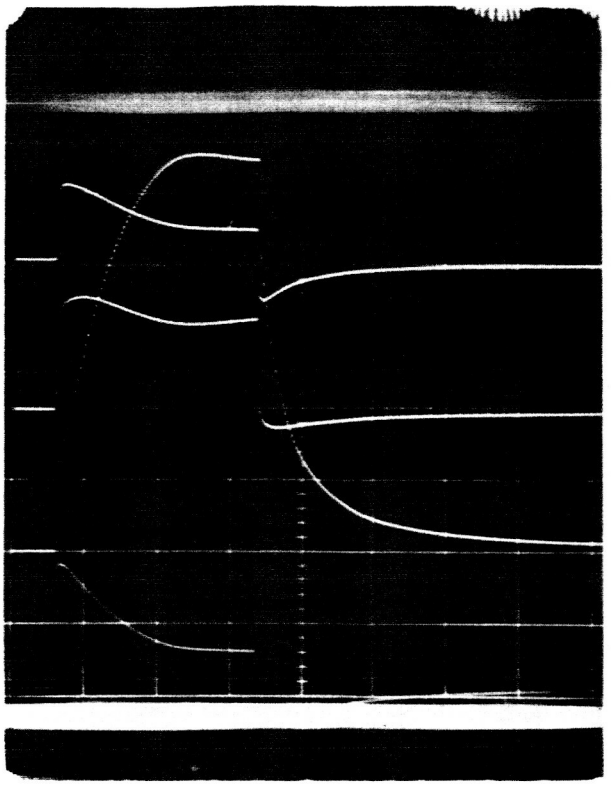

Figure 10. Oscilloscope photograph of current pulse from a single stimulator, split through four electrically parallel electrode segments, at the moment of first report of pain (the single common indifferent electrode was on the sole of the foot.) Moments before, at 0.3 ma. lower intensity, all four pulses were rectangular and the same size. Notice that the peak current through one segment is several times higher than that through the others, indicating tissue breakdown under one electrode segment on the dorsal forearm as the cause of the stinging pain.

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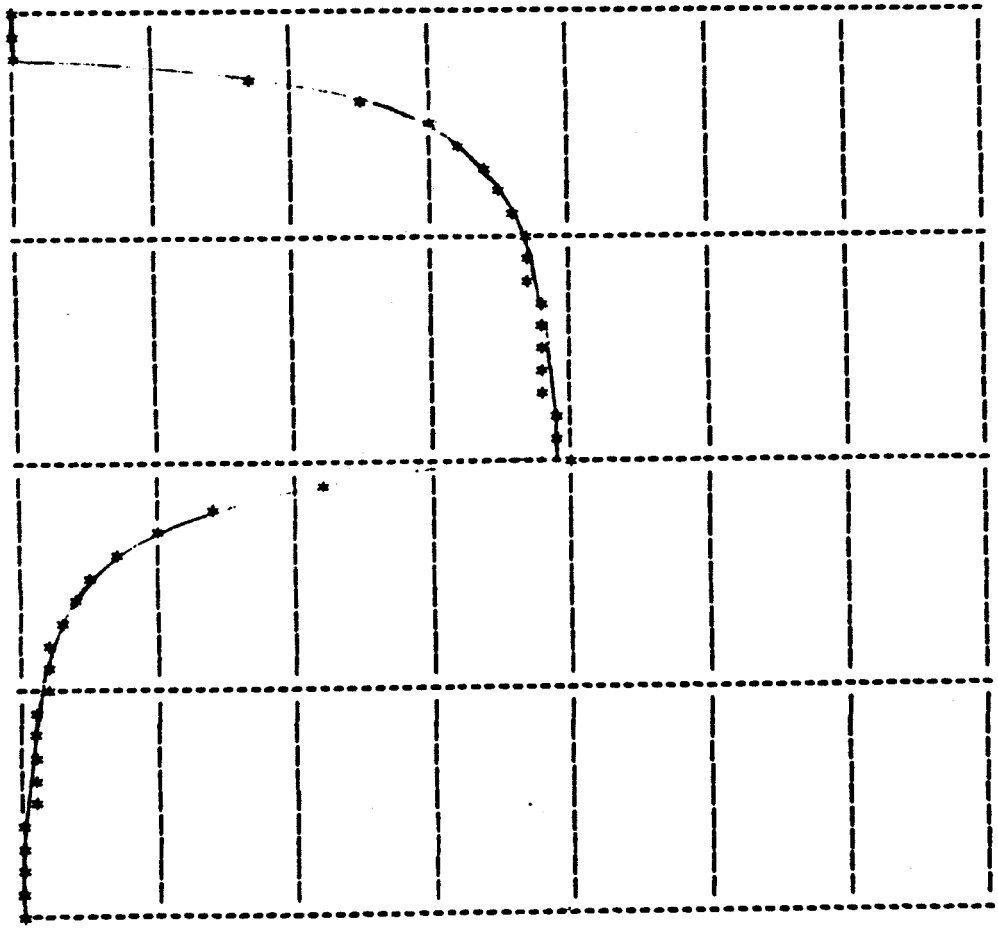
AN USER G446.119; PROGRAM 1/5;
AN RUN,ALGOL,TAPE; DONE;
                                                    GIBSON, R. H.
                                                    TIME: 00:00:03
                                        'AND' RECORD SOURCE     21:54:59
                                                    00:00:05

AL      15710  BEGIN INTEGER X,Y,Z; Y←0;
AL      15713  FOR X←0 STEP 1 UNTIL 50 DO BEGIN
        15734  IF X=10 THEN Y←10; IF X=30 THEN Y←0;
        15750  PRINT (<1C>,→8<'|',9R>);
        15772  IF ↓(X/10)=(X/10) THEN PRINT (<1C>,→71<'-'>);
        16024  IF X>29 THEN BEGIN
AL      16031  PRINT (<1C>,
        16036   →$(40/(((X/3)-9)*((X/3)-9)))$<R>,<'*',E>);
        16067  GO SKIP; END;
        16071  IF X>9 THEN
AL      16076  PRINT (<1C>,
        16103   →$↓(40-(40/(((X/3)-3)*((X/3)-3))))$<R>,<'*',E>);
        16136  SKIP: END;
        16137  END;
                                                    00:00:05
```



```
        TIME USED:  00:00:13    PAGES USED:    1          '  21:55:09
22:02:22  END OF RUN
```

Figure 11. Computer program and printout of simulated voltage pulse. This is output from a rectangular, 2 msec., 1 ma. current pulse delivered to a circuit with equations simulating electrical properties of human tissue.